Enhanced Direct-Drive Implosions with Thin High-Z Ablation Layers

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Abstract

New direct-drive spherical implosion experiments with deuterium filled plastic shells have demonstrated significant and absolute (2x) improvements in neutron yield when the shells are coated with a very thin layer (~200-400Å) of high-Z material such as palladium. This improvement is interpreted as resulting from increased stability of the imploding shell. These results provide for a possible path to control laser imprint and stability in laser-fusion-energy target designs.

With the advent of modern laser smoothing technology [1, 2], efficient direct-drive laser fusion has become a viable option [3]. Smoothing reduces high power laser intensity non-uniformities that can seed hydrodynamic instabilities and lead to premature destruction of imploding fusion pellets. Without good intensity smoothing, indirect target illumination methods are necessary. This led to the early adoption of schemes where laser energy is converted into more uniform x-ray drive in “hohlraum” blackbody-like cavities [4]. Indirect illumination enhances short wavelength uniformity but at the price of increased complexity and reduced efficiency. While current direct drive approaches can produce the necessary uniformity, this is done with statistical averaging that is only effective for times that are long compared to the laser coherence time. As a result, in the first tens of picoseconds of a laser-target interaction, when the laser is absorbed on the surface of the target, the combination of lower laser uniformity and the lack of pressure smoothing from a stand-off plasma creates the potential of non-uniform imprinting of the target. The imprint is small, but simulations and experiments show that it can be important in seeding instability growth.

In various previous works, hybrid schemes have been considered where initial x-ray illumination reduces the imprint of directly driven targets [5,6,7]. More recently, in work at NRL’s Nike facility, Obenschain et al.,[8] showed that direct drive laser imprint can be virtually eliminated in planar targets through the use of shaped laser pulses and thin high-Z layer ablation coatings. Under initial low-intensity laser illumination, the high-Z ablation layers expand and convert the initial non-uniform laser flux into uniform x-ray radiation that uniformly ablates and accelerates the target. As the laser pulse shifts to higher intensities, the high-Z material burns away and the target transitions to pure direct drive. By this method, indirect x-ray drive is used during the non-uniform start-up phase while direct drive is employed during the remaining more uniform phases of the drive pulse.

In this letter, we report the first use of the high-Z ablation layer technique in spherical implosions. We demonstrate significant increase in the fusion yield and find good control of the yield via the thickness of the high-Z layer. With increasing layer thicknesses, 200-400 Å, the absolute yield can be increased by a factor of two, while the yield relative to ideal 1D simulations increases from 3% to 55%. Fusion yield from imploding targets is used as the primary method for evaluating the efficacy of the high-Z ablation layers. Plastic shell targets filled with deuterium (D_2) gas (Figure 1) are imploded by the 60 beams of the SSD smoothed Omega laser at the Laboratory for Laser Energetics [9]. The beams are frequency tripled to 351 nm and THz bandwidth is used for SSD smoothing. The imploding shells compress the gas to sufficiently high density (~1-5gm/cm^3) and high temperatures (~2-10KeV) such that a small fraction of the D_2 nuclei to undergo DD fusion and produce energetic neutrons. Time-of-flight detectors are used to quantify the fusion yield and ignition timing. In parallel, the dynamics of the implosion and target radiation properties are monitored with time resolved x-ray imaging and spectral diagnostics.

The experimental parameters for evaluating the above processes were set by 1D simulations of spherical implosions for various prospective target designs and the capabilities of the Omega laser. The target dimensions are matched to the focal size of the Omega laser beams, whereas the choices of shell thickness and laser pulse profiles represent a compromise between high implosion efficiency and stability of the imploding shell. With a thin shell (~20μm) and a shaped laser pulse designed to drive the uncoated target on a low adiabat, we ensure that our experiment is sensitive to target breakup as a result of hydrodynamic instability. Experiments were executed over a range of parameters spanning the design space. Spherical target shells were constructed from CH and CD plastic and were filled with 3 and 15 atmospheres of D_2. High Z-layers with 200Å, 400Å, 600Å, and 800Å of palladium (Pd) were applied to the targets and the targets where driven with laser pulse shapes having a short or long initial intensity foot (Figure 1).

Data are obtained from a set of 24 Omega shots. In initial shots, CD shells (D ~ 860μm, 20μm thick) with 3 atm of D_2 are imploded with the long foot pulse. Two shots are taken for each condition of 0Å, 200Å, and 400Å thick Pd layers. The measured neutron yield is plotted in Figure 2. The data are reproducible and show a statistically significant increase in neutron yield with increases of Pd layer thickness. The measurement error is estimated at being lower than +/-10% and is indicated with representative error bars. For the 400Å thick Pd layers, we find a factor of two increase in neutron yield. It is interesting to compare this to recent parallel efforts [10] where comparable target implosion performance improvements where achieved with picket pulse shaping of the target adiabat.

In the analysis of our data, the experiments are simulated with the FAST 1D hydrodynamic code [11]. As required by our high-Z conditions, the code uses non-LTE radiation transport in 45 distinct wavelength groups. A diffusion model is used for the radiation transport whereas non-LTE physics is modeled via the Busquet model [12] and opacities are calculated using the STA model [13]. Heat transport is performed using a harmonic flux-limiting value of 0.1 and the laser deposition is based on inverse Bremsstrahlung absorption with ray-tracing. Finally, the simulations are started with an initial 50-100x pre-expansion of the high-Z layer.

1D predictions of the neutron yield are indicated along the data in Figure 2 as the ratio of the true yield to the 1D calculated yield, commonly known as the yield over clean (YOC) ratio. For targets with no Pd layer, YOC ~ 3%, whereas with Pd, we find that YOC ~ 55%. These results are interpreted in terms of true 3D unstable behavior of the Pd-free target implosion and the reduction of implosion efficiency due to x-ray heating of the target and x-ray energy losses of the Pd-coated implosion. With no Pd and minimal x-ray heating, the ideal 1D thin-shell implosion proceeds at higher implosion velocities, higher densities and on a lower adiabat (α=*pressure/Fermi pressure*). High velocity, high density shells deliver more impulse and produce higher hot spot pressures at the stagnation point. In Figure 3, calculations of the adiabat at the end of the drive pulse (1ns foot case) are presented as a function of Lagrangian mass. The peak stagnation pressure is also noted. Uncoated targets maintain an $\alpha \sim 2$-3 adiabat for an in-flight target thickness less than 10 microns. In contrast, high-Z coated targets implode on a much higher adiabat with $\alpha \sim 5$-15. While characterizations in terms of the adiabat are important for comparing to other experiments and simulations, the standard scaling laws [14] used to characterize fusion ignition requirements are not strictly applicable to gas filled CD or CH shell targets. While the final stagnation pressure and the resulting fusion yield is sensitive to the shell density and the impedance matching of shocks at the hot-spot/shell interface, the plastic shell targets differ from true fusion targets in that they do not carry fusion fuel that can produce or propagate burn.

For ablatively accelerated targets, the Rayleigh-Taylor instability growth rate is given by $\gamma \approx 0.9\sqrt{kg} - \beta k V_a$, where k is the mode number, g is the acceleration, V_a is the ablation velocity, and $\beta \sim 3\text{-}4$ [15]. Thin, low adiabat targets are particularly susceptible because their higher densities reduce the ablation velocity and its stabilization, while the short wavelength modes that are efficient at breaking up the shell $k \sim 2\pi/shell\ thickness$ have the highest growth rates. With large potential instability growth, discrepancies between experiment and ideal 1D simulations are expected for the uncoated targets. If instability is reduced by high-Z layers, then target yield is expected to come closer to 1D predictions. By itself, increases in the (YOC) ratio are insufficient to indicate an improvement in stability because x-ray preheat will increase the target adiabat, thus reducing the maximum compression, the 1D implosion efficiency, and the calculated 1D yield. The fact that the absolute neutron yield is increased, in spite of reductions in implosion efficiency, indicates that improvements in target stability due to reductions in Rayleigh-Taylor growth or initial target imprint had to have occurred as a result of the radiation from the high-Z layers.

The applicability of the hydrodynamic code simulations was tested by a comparison of the implosion trajectory with 1D calculations. Figure 4 shows the x-ray emission radius of an imploding 20μm thick, 3 atm D_2 filled shell targets, with and without a high-Z layer, as measured by an early and late time pinhole x-ray framing camera. The computed trajectories correspond to the peak shell density. The error in radial position is estimated to be about +/- 5%, whereas time is resolved to within 50 ps [16]. At early times, the data are in very close correspondence to the 1D simulations. The later time data show the shell diameter reaching its final implosion diameter almost 500ps before the simulated time. As observed in previous shock yield experiments [17], this is explained by the presence of a converging shock that is launched in the fill gas ahead of the accelerating shell. Shock convergence in the center produces strong heating and x-ray emission. On average, the measured core diameter appears larger than predicted by the simulations, perhaps indicating shell breakup in pure CD targets and thicker higher adiabat shells in high-Z layer targets.

In a second set of shots, measurements are extended to thicker Pd layers. CH shells (D ~ 860μm, 20μm thick) with 3 and 15 atm of D_2 are imploded with the short foot pulse. The shorter pulse provides better shock timing. Shots are taken for each condition of 0Å, 200Å, 400Å, 600Å, and 800Å thick Pd ablation layers. The yield results are shown in Figure 5. As before, yield improves with Pd thickness for thin layers, but beyond 400Å, presumably due to increased x-ray preheat, improvements saturate and decay sharply for 800Å thick layers. For general applicability, data points were also taken with higher fill pressure targets (p ~ 15 atm D_2). The absolute yield is higher but basic target performance and 2x maximum improvement in yield is similar to what is observed at lower fill pressures.

Finally, it is of interest to test the extent that the high-Z layer method can overcome large initial intensity non-uniformity. This is evaluated by turning off individual beams to produce long spatial scale non-uniformities and by reducing the bandwidth of SSD smoothing to produce short scale non-uniformities. In Figure 5, the datum point for the target with 3 atm fill pressure and of 400Å Pd thickness was shot with one beam turned off. To 1st order, this is expected to reduce the intensity on one side of the target by about 3%. At this level, yield is not significantly reduced but if four adjacent beams are turned off, as in the low lying datum point of the high pressure data in Figure 5, the intensity on the off side is reduced by 13% and the neutron yield falls precipitously. In contrast, short scale non-uniformities are much more amenable to the benefits of high-Z layers. Figure 3 shows data (square datum points) from shots where the SSD bandwidth is reduced by about a factor of two. With SSD, short scale intensity non-uniformity scales as $(1/\text{bandwidth})^{1/2}$, thus non-uniformity is expected to be increased by about 40%. In spite of this large bandwidth reduction, the neutron yield does not fall significantly for targets with 200Å and 400Å Pd layers. The smoothing from high-Z layers is sufficient to overcome the increases in laser non-uniformity. By turning off the SSD modulation with the SSD phase plates in place, it is possible to produce large stationary speckle patterns on target that increase non-uniformity by an order of magnitude[18] over that of full SSD averaged over the length of the laser pulse. Under these conditions, the neutron yield falls precipitously (3x) for targets with and without high-Z layers.

While the experiment shows clear improvements in target stability with the high-Z layers, calculations show that the thin targets with high-Z layers could not be driven on a low adiabat under our experimental conditions. This is primarily due to the small scale of the experiment where the low intensity foot pulse has to be relatively short and is not indicative of conditions that would be expected under reactor conditions. In calculations for reactor scale pellets[19], where the target shell thickness and the foot pulse length are increased by an order of magnitude, the high-Z layer can easily be decompressed to sufficiently low densities such that radiation from the high-Z material plays a minor role during the high intensity portion of the laser pulse.

In summary, we have conducted laser driven spherical implosion experiments with thin shell fusion pellets filled with D_2 gas and have demonstrated that it is possible to increase the neutron yield performance of these targets with the use of high-Z ablation layers. Absolute neutron yields can be increased by a factor of two, while YOC is increased form a few % to beyond 50%. These improvements are interpreted as indicators of increased target stability. The high-Z layers are most effective against short wavelength perturbations, easily compensating for increases in non-uniformity from a large (2x) reduction of SSD modulation bandwidth. Fusion yield improvements are comparable to the recent results from work with picket-pulses to shape the target adiabat. Both approaches work to reduce imprint and hydrodynamic instability growth. It is clear that multiple new methods are now available for improving the stability and implosion performance of directly driven fusion pellets.

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Figure Captions

1. Plastic shell targets are filled with high-pressure D_2 fuel and are driven with shaped laser pulses designed to minimize shock heating of the shell. Thin high-Z layers of Pd metal produce sufficient x-rays in the early parts of the laser pulse to drive the targets with x-ray ablation and minimize laser imprinting of the target.
2. Neutron fusion yield from targets filled with 3 atm of D_2. Absolute neutron yield and YOC increase with increases of the Pd layer thickness. An absolute increase indicates that the high-Z layers improve the stability of the targets. The high-Z layers are effective in improving target stability even for large reductions in SSD smoothing.
3. Calculations of the target adiabat with and without the high-Z layers.
4. Target implosion trajectory as measured by x-ray framing diagnostics and calculated by the FAST 1D code.
5. Data set of neutron yield measurements from target implosions as a function of high-Z layer thickness for 3 and 15 atm of D_2 fill gas. Data show the saturation in target yield as a result of very significant x-ray heating of the targets for thick high-Z ablation layers. Also shown is the effect of low mode number asymmetry as a result of turning off one 4-beam laser cluster.

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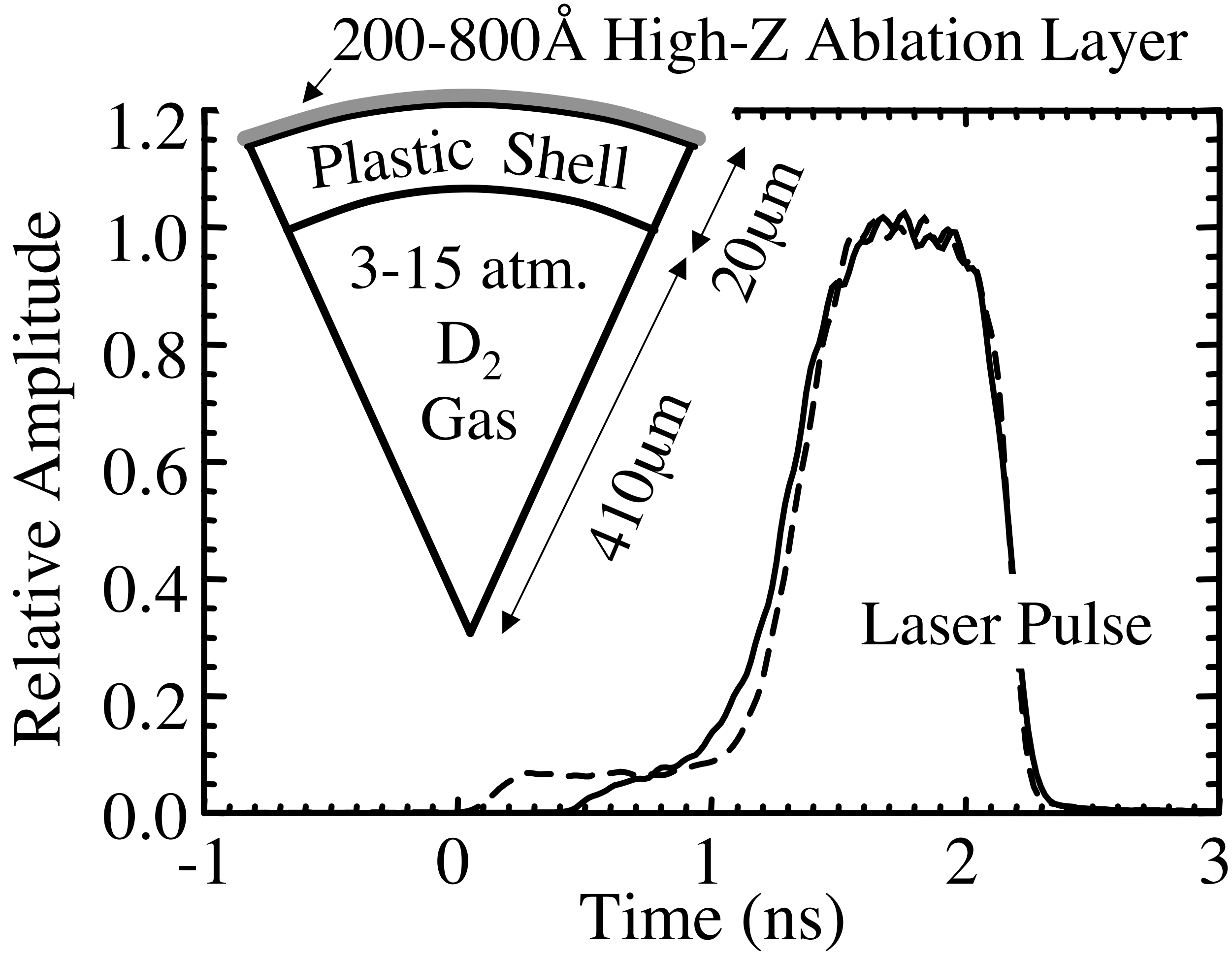
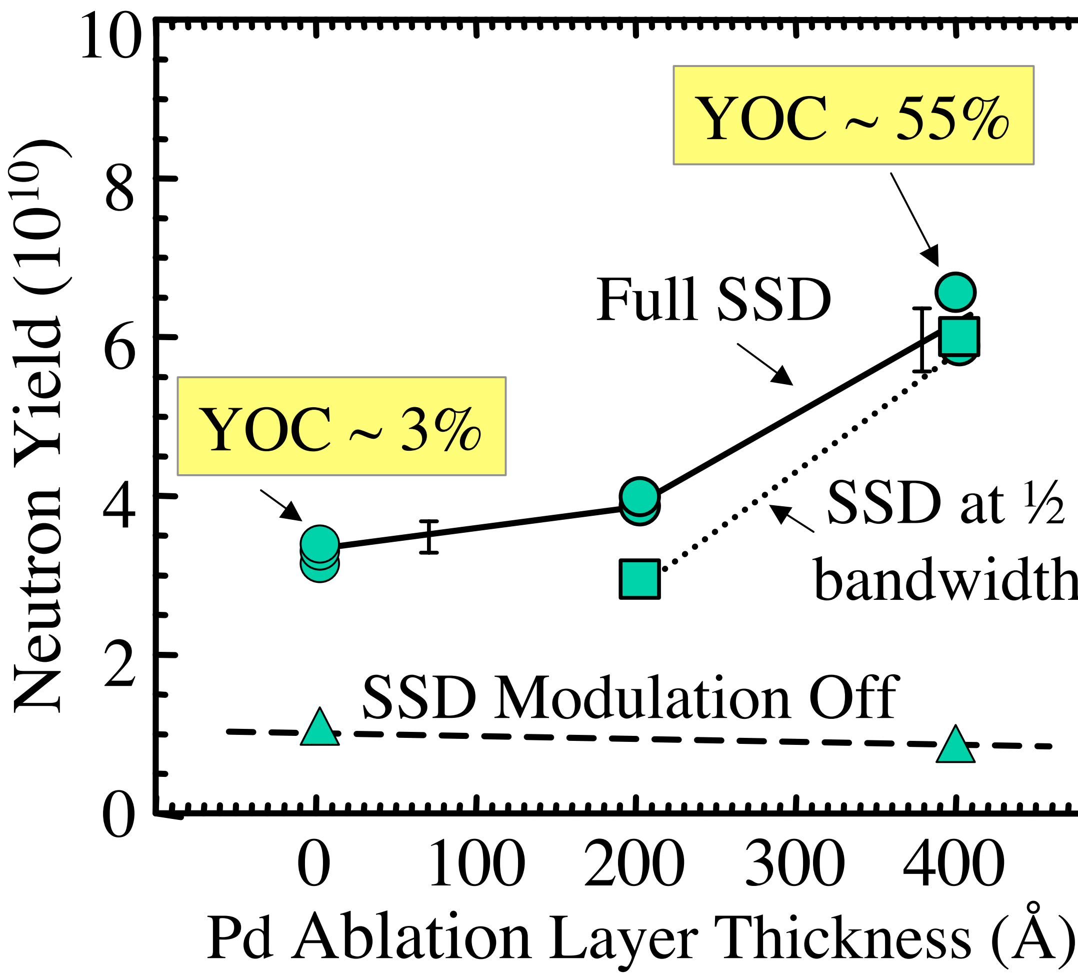


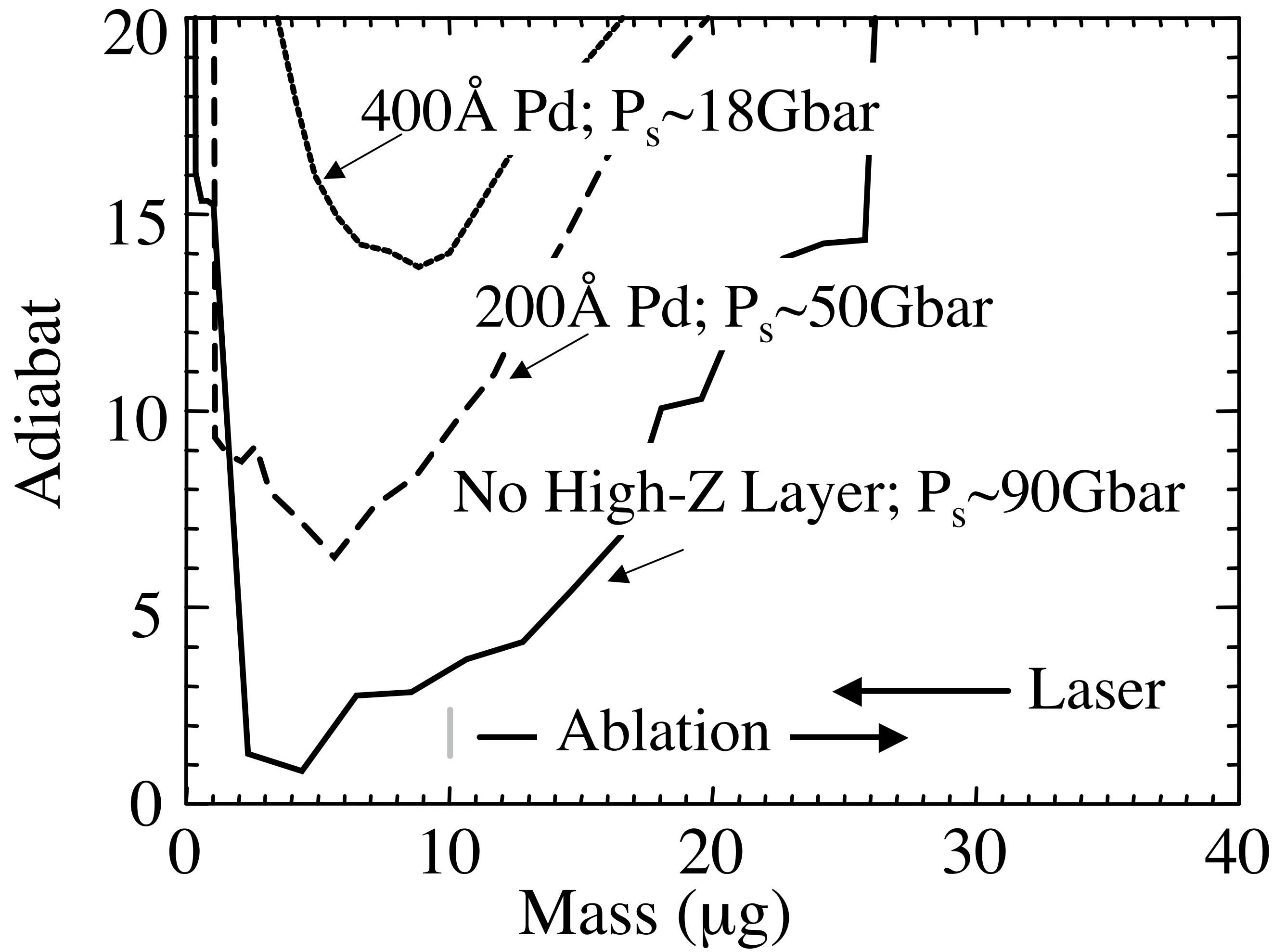
200-800Å High-Z Ablation Layer
Plastic Shell
3-15 atm.
D_2
Gas
20μm
410μm
Laser Pulse
Relative Amplitude
0.0
0.2
0.4
0.6
0.8
1.0
1.2
-1
0
1
2
3
Time (ns)

Figure 1.



YOC ~ 55%
Full SSD
YOC ~ 3%
SSD at ½ bandwidth
SSD Modulation Off
10
8
6
4
2
0
0
100
200
300
400
Neutron Yield (10^10)
Pd Ablation Layer Thickness (Å)

Figure 2.



400Å Pd; Ps~18Gbar
200Å Pd; Ps~50Gbar
No High-Z Layer; Ps~90Gbar
Laser
Ablation
Adiabat
Mass (μg)
0
5
10
15
20
0
10
20
30
40

Figure 3.

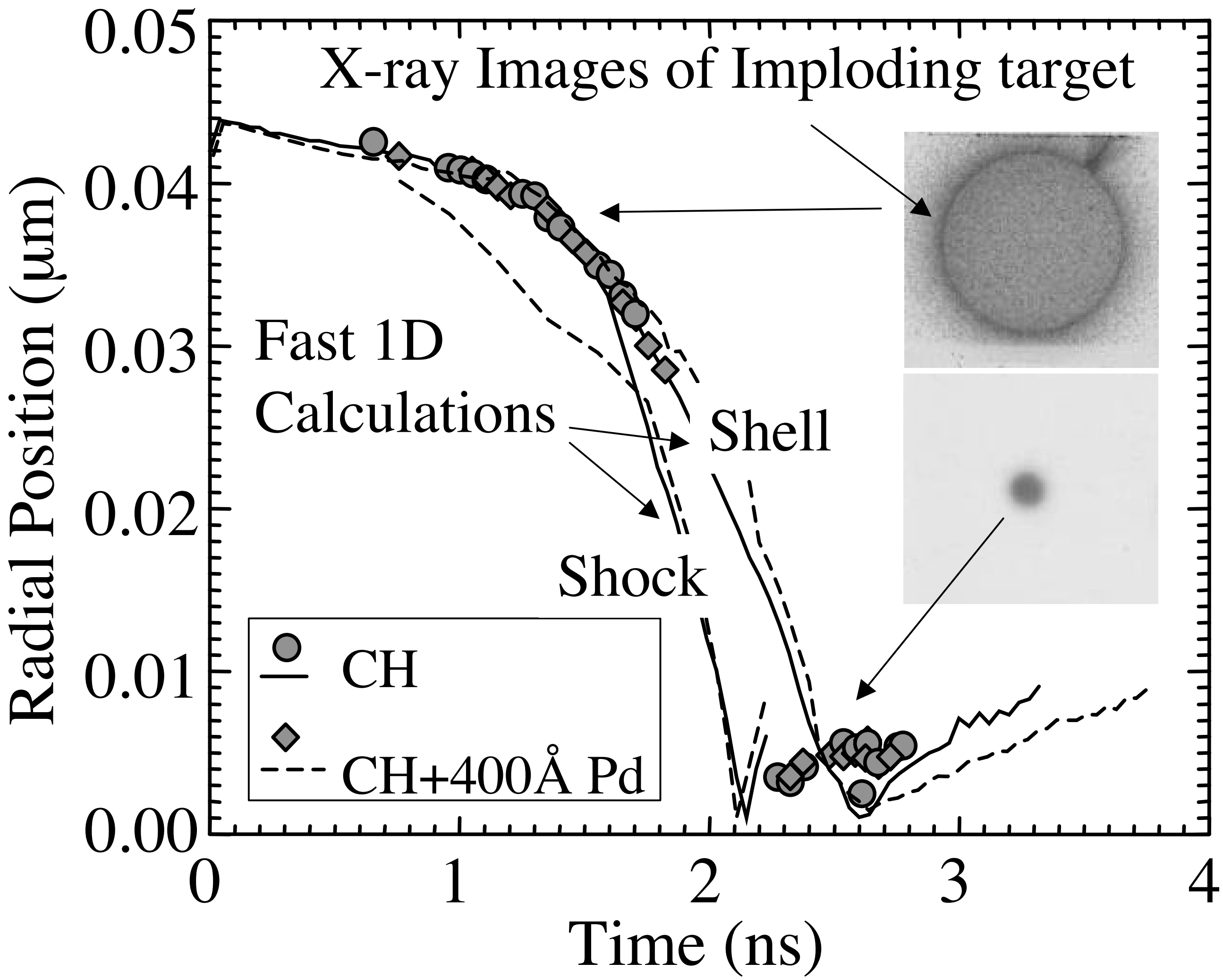

X-ray Images of Imploding target
Fast 1D
Calculations
Shell
Shock
CH
CH+400Å Pd
Radial Position (μm)
Time (ns)
0.05
0.04
0.03
0.02
0.01
0.00
0
1
2
3
4

Figure 4.

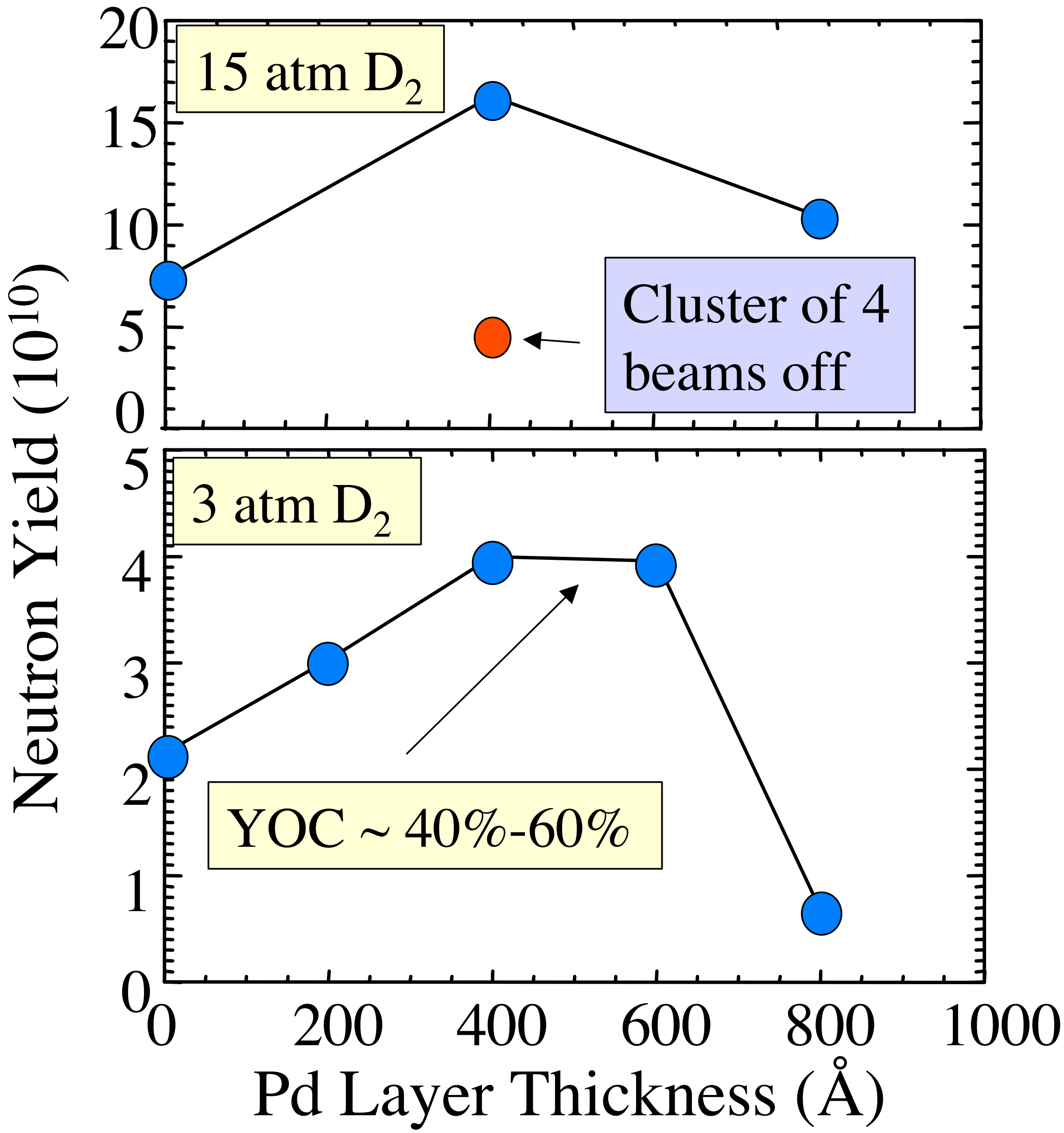

15 atm D_2
Cluster of 4
beams off
3 atm D_2
YOC ~ 40%-60%
Neutron Yield (10^{10})
Pd Layer Thickness (Å)
0
5
10
15
20
0
1
2
3
4
5
0
200
400
600
800
1000

Figure 5.